Numerical Analysis Of Circular Concrete-Filled Stainless Steel Tubular Short Columns Under Axial Loading

Mizan Ahmed¹, Soheil Gohari², Khaled Sennah³, Wensu Chen¹

¹School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia
²Department of Mechanical Engineering, The University of Melbourne, Parkville, VIC 3010, Australia
³Department of Civil Engineering, Ryerson University, Toronto, Canada
mizan.ahmed@curtin.edu.au; soheil.gohari@unimelb.edu.au; ksennah@ryerson.ca; wensu.chen@curtin.edu.au

Abstract – This paper develops a simplified fiber-based numerical model to investigate the performance of circular concrete-filled stainless steel tubular (CFSST) short columns subjected to axial loading. A new compressive concrete strength formula is developed based on the test data of CFSST columns. The accuracy of the numerical model is evaluated by comparing the ultimate axial capacity and axial load–strain curves of CFSST columns with a large test database. A parametric study is carried out to investigate the effects of geometry and material properties on the axial performance of CFSST columns.

Keywords: Concrete-filled steel tubes; axial loading; short columns; nonlinear analysis.

1. Introduction

The composite action between the steel and concrete of concrete-filled steel tubular (CFST) columns results in improved structural performance in terms of strength, ductility, fire and seismic resistance compared to that of reinforced concrete columns. The lateral confinement inserted by steel tube to the confined concrete is more effective in CFST counterparts, thus widely used in the construction of high-rise buildings and bridge piers to carry large axial loads [1]. However, the steel tube of CFST columns may be subjected to corrosion which may reduce their axial performance. As stainless steel offers excellent corrosion resistance, circular concrete-filled stainless steel tubular (CFSST) columns were proposed. Owing to the distinguished strain hardening behavior of stainless steel, the performance of CFSST columns is different than that of CFST columns with carbon steel. In addition, the cost-effective design of CFSST columns is important considering the higher cost of stainless steel than carbon steel. However, there is a lack of research in the development of an accurate numerical model to study their axial performance.

Test on circular CFSST short columns subjected to axial loading was carried out by [2-14]. The test results showed that CFSST columns have higher ultimate strength and ductility compared to that CFST columns. The experimental program reported in the literature examined the influences of a wide range of column parameters of CFSST columns under axial loading including the tube diameter [2-4, 6-8, 10, 12, 15], tube thickness [4, 6, 8, 12, 14], concrete strength [2-4, 6, 7, 11, 14], recycled aggregates [5, 9], and column slenderness ratio [3, 10-12]. The axial behavior of CFSST columns was numerically investigated by [13], [15], [16], [17] and [18]. Patel et al. [16] concluded that the conventional lateral pressure model for carbon steel underestimated the axial performance of CFSST columns. However, until today no effort was made to develop a lateral pressure model for CFSST columns.

This paper develops a numerical model using a fiber model to investigate the axial performance of CFSST short columns under axial loading. An accurate formula to predict the compressive strength of concrete of CFSST columns is developed based on the existing experimental data. The accuracy of the numerical prediction is validated using a large test database comprising of test data of 125 short columns. A parameter study is carried out to study the influences of geometry and material properties of CFSST columns on their axial performance.

2. Numerical Model
The numerical model is developed using the fiber analysis theory, where the cross-section of the CFSST column is divided into small fibers, as shown in Fig. 1. The fibers either represent the properties of stainless steel or concrete based on the uniaxial material laws assigned to them. The computational analysis starts with initializing a small axial strain and then calculating the stresses occurring in fibers using the uniaxial material laws assigned to them. The column axial load (\( P \)) is calculated as the resultant stress. The theoretical analysis continues for the increase of the axial strain until the maximum column axial load (\( P_{\text{ult}} \)) is achieved. The stopping criterion is chosen when \( P \) drops to \( 0.5P_{\text{ult}} \) or the axial strain exceed the prescribed ultimate strain of concrete (\( \varepsilon \geq \varepsilon_{\text{cu}} \)). The analysis steps to predict the full axial load-strain (\( P - \varepsilon \)) curves of CFSST columns are given as follows:

1. Input details of CFSST column.
2. Divide the cross-section into fine fibers.
3. Initialize strain as \( \varepsilon = \Delta \varepsilon \).
4. Calculate fiber stresses using the material uniaxial stress-strain relationships.
5. Compute the axial force \( P \) as the stress resultant.
6. Increase axial strain by \( \varepsilon = \varepsilon + \Delta \varepsilon \).
7. Repeat Steps 4 to 6 until \( P \leq 0.5P_{\text{ult}} \) or \( \varepsilon \geq \varepsilon_{\text{cu}} \).
8. Plot \( P - \varepsilon \) curve.

Fig. 1: Discretization of the cross-section of a CFSST column in fiber analysis method.

3. Material properties

3.1 Stainless steel

The stress-strain relationships of stainless steel proposed by Quach et al. [19] are adopted in this study. The original formulae proposed by Quach et al. [19] to calculate the full stress-strain curves of stainless steel is stress-dependent. Abdella et al. [20] suggested formulae to derive the inverse version of the stress-strain relationships of stainless steel proposed by Quach et al. [19] to calculate the full ranges of the tensile and compressive stresses of stainless steel in the function of strain. The three-stage stress-strain relationships of stainless steel developed by Quach et al. [19] provide a better estimation than the existing two-stage constitutive laws of stainless steel [16, 21].

3.2 Concrete
Figure 2 illustrates the stress-strain relationships of concrete adopted in this study [22]. The axial stress of concrete \( \sigma_c \) at the ascending branch of the curve is calculated using the formulae developed by Mander et al. [23]:

\[
\sigma_c = \frac{f_{cc} (\varepsilon_c / \varepsilon_{cc}) \lambda}{(\varepsilon_c / \varepsilon_{cc})^2 + \lambda - 1}
\]

for \( 0 \leq \varepsilon_c \leq \varepsilon'_{cc} \) 

\[
\lambda = \frac{E_c \varepsilon_{cc}}{E_c \varepsilon_{cc} - f_{cc}}
\]

where, \( \varepsilon_c \) is the concrete strain; \( f_{cc} \) and \( \varepsilon_{cc} \) are the concrete compressive strength and the corresponding strain, respectively; \( E_c \) is the elastic modulus of concrete, calculated as [22]:

\[
E_c = 4400 \sqrt{f_{cc}}
\]

The column size on the compressive strength of unconfined concrete \( (f_{cc}^-) \) is considered using a reduction factor \( (\gamma_c) \), developed by Liang [24] as \( \gamma_c = 1.85 D^{0.135} \), where, \( D = D - 2t \), in which \( D \) and \( t \) are the diameter and thickness of the steel tube, respectively.

As discussed earlier, the lateral confinement provided by the steel tube improves the strength and ductility of the confined concrete which is considered in the stress-strain relationships of concrete. A new formula to calculate the compressive strength of concrete \( (f_{cc}^-) \) of CFSST columns is developed by analyzing the existing test data of CFSST columns. Parameter study demonstrates that \( f_{cc}^- \) is influenced by the confinement factor \( (\xi) \), which can be calculated as \( \xi = \frac{\sigma_{0.2}}{A_s / A_c f_{cc}^v} \), where, \( \sigma_{0.2} \) is the yield stress of stainless steel taken as 0.2% proof stress; \( f_{cc}^v \) is the compressive strength of unconfined concrete; \( A_s \) and \( A_c \) are the area of steel and concrete, respectively. The test compressive strength of confined concrete \( (f_{cc, test}) \) of tested columns is determined by subtracting the axial capacity of the stainless steel tube from the ultimate axial load of CFSST columns. Based on the regression analysis, a formula to calculate the compressive strength of confined concrete is proposed herein as:

\[
\frac{f_{cc}}{f_{cc}^-} = 0.44 \xi + 0.9 \geq 1.0
\]

Wang et al. [25] suggested a formula to calculate the compressive strain of confined concrete \( (\varepsilon_{cc}^-) \):
The axial stress of concrete at the descending branch of the stress-strain curves is calculated using the formula developed by Lim and Ozbakkaloglu [22] as:

\[
\sigma_c = f_{cc} - \frac{f'_{cc} - f_{cr}}{1 + \left( \frac{\varepsilon_{c} - \varepsilon_{cc}}{\varepsilon_{ci} - \varepsilon_{cc}} \right)^2}
\]

for \( \varepsilon_c > \varepsilon_{cc} \)  \( \text{for } 1 < \beta_c \leq 1.0 \) \( \beta_c = 1.2420 - 0.0029 \left( \frac{D}{t} \right) - 0.0044 f_c' \)  \( \text{for } \varepsilon_{ci} \) \( \varepsilon_{ci} = 2.8 \varepsilon_{cc} \left( f_c' \right)^{-0.12} \left( \frac{f_{cr}}{f_{cc}} \right) + 10 \varepsilon_{cc} \left( f_c' \right)^{-0.47} \left( 1 - \frac{f_{cr}}{f_{cc}} \right) \)

The strain at the inflection point \( \varepsilon_{ci} \) is calculated as [22]:

\[\varepsilon_{ci} = 2.8 \varepsilon_{cc} \left( f_c' \right)^{-0.12} \left( \frac{f_{cr}}{f_{cc}} \right) + 10 \varepsilon_{cc} \left( f_c' \right)^{-0.47} \left( 1 - \frac{f_{cr}}{f_{cc}} \right) \]

4. Validation

The numerical model is validated by comparing the predicted ultimate load and \( P - \varepsilon \) curves of CFSST columns with the ones obtained from the test study. A total of 125 test data is used for validation purposes. The comparison between the test and predicted ultimate load of CFSST columns is shown in Fig. 3, where it can be seen that the numerical model can provide a reasonable estimation of the ultimate strength of CFSST short columns subjected to axial loading. From Fig. 4, it also can be seen that the numerical model can accurately predict the \( P - \varepsilon \) curves of CFSST columns.

Fig. 3. Comparison of the predicted ultimate strength of CFSST columns with the experimental results.
5. Parametric study

The validated numerical model is used to carry out a parameter study to investigate the effects of diameter-to-thickness (\(D/t\)) ratio, concrete compressive strength and the yield stress of steel on the axial performance of CFSST columns. The details of the reference column are as follows: \(D = 500\) mm; \(t = 10\) mm; \(f'_c = 50\) MPa, \(\sigma_{0.2} = 205\) MPa.

5.1 Effects of the diameter-to-thickness (\(D/t\)) ratio

The \(D/t\) ratio of the CFSST column is an important column parameter that influences their axial performance. In this study, the thickness of the steel tubes is changed to vary the \(D/t\) ratio from 25 to 100. As illustrated in Fig. 5, it was found that increasing the \(D/t\) ratio from 25 to 100 decreases the ultimate load of CFSST columns by 51.4\%. This is because decreasing the thickness of the steel tube wall reduces the confinement effect. The ductility of the CFSST column is also decreased as the \(D/t\) ratio increases, as can be seen in Fig. 5.
5.2 Effects of concrete compressive strength

The influences of concrete strength on the axial performance of the CFSST column are investigated by changing the concrete strength from 25 MPa to 100 MPa. It is seen from Fig. 6 that increasing concrete strength increases the axial capacity of the columns. When concrete strength increases from 25 MPa to 100 MPa, the ultimate load is increased by 79.2%. However, increasing concrete strength decreases the ductility of the columns. This is due to the brittle nature of high-strength concrete.

5.3 Effects of steel yield stress

To study the effects of steel yield stress, the axial performance of the CFSST column is investigated for different grades of stainless steel, namely austenitic, ferritic and duplex stainless steel. The yield stress of the austenitic, ferritic and duplex stainless steel are taken as 205, 275 and 430 MPa, respectively based on suggestions given in AS/NZS 4673-2001 [27]. It is found that with a steel yield stress increased from 205 MPa to 430 MPa, the ultimate load of the CFSST column is increased by 48.1%, as illustrated in Fig. 7. However, the steel yield stress has insignificant effects on the ductility of the CFSST column.
6. Conclusion

This paper develops a numerical model to study the performance of CFSST columns under axial loading. A new formula to calculate the compressive strength of concrete is developed based on the existing test data. Upon validation, the numerical model is used to perform a parametric study to study the effects of the \( D/t \) ratio, the yield stress of steel and concrete strength on their axial performance. It is found that the numerical model can accurately predict the axial performance of the CFSST column observed experimentally. The parametric study shows that increasing \( D/t \) ratio reduces the ultimate load of CFSST columns whereas increasing the yield stress of steel or concrete strength increases their ultimate load. However, the ductility of the CFSST column is reduced as the \( D/t \) ratio or the concrete strength increases.

References